SOFTWARE DETERMINATION OF LED BRIGHTNESS AND EXPOSURE

CROSS REFERENCE TO RELATED APPLICATIONS

A related copending United States patent applications commonly owned by

5   the assignee of the present document and incorporated by reference in its entirety into

this document is being filed in the United States Patent and Trademark Office on or

about the same day as the present application. This related application is Hewlett-

Packard docket number 10991888, serial number _____, and is titled

"HARDWARE MODELING OF LED RELATIVE BRIGHTNESS."

10   ## FIELD OF THE INVENTION

The invention relates generally to precision control of an exposure and more

particularly to modeling the light output of a light emitting diode (LED) to maintain a

constant exposure as the light output of an array of LED's changes over temperature

and the lifetime of the part.

15   ## BACKGROUND OF THE INVENTION

High quality image capture such, as grayscale and color imaging, needs a

precision light source. Because of their size, price, reliability, and other qualities,

light emitting diodes (LED's) may be chosen as the light source for image capture.

Unfortunately, the light output of an LED changes with junction temperature and age. Because LED's heat up when they are on, one of the factors that determines the junction temperature of an LED, and hence its light output, is the amount of time, and duty cycle, that the LED is on. One way to compensate for at least part of this

5   variation is to use a light calibration strip. A light calibration strip may be used with a search algorithm to set the illumination levels prior to image capture. A disadvantage of this method is that part of the image capture array is used to sense the calibration strip. This decreases the width or area that is captured at any given moment. Another disadvantage is that this method does not account for changes in the junction

10   temperature during image capture.

Accordingly, there is a need in the art for an illumination compensation method and apparatus that does not utilize a light calibration strip.

SUMMARY OF THE INVENTION

An embodiment of the calculates the LED light output given a set of

15   calibration values, the ambient temperature, the recent on-off history of the device, and the long term history of the device. Once the LED light output is calculated, an exposure can be calculated that will be nearly constant over the operating conditions and lifetime of the device. The ambient temperature is obtained from a temperature sensor. The recent on-off history of the device is timed with a counter-timer. The

20   long-term history of the device and the calibration values are recorded in non-volatile memory. The calibration values are measured and set at the time of manufacture and ensure that each device produces nearly the same exposure under the same conditions.

Other aspects and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying

25   drawings, illustrating by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a capture exposure system.

FIG. 2 is a flowchart illustrating steps used to calculate illumination and exposure.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is a block diagram of a capture exposure system **100**. Central processing unit (CPU) **110** sends illumination control signal **116** to LED driver **112** and LED model **102**. LED driver **112** is coupled to LED array **114**. LED array **114** provides illumination for capturing an image. This capture exposure system also has an ambient temperature sensor **106**. The output of ambient temperature sensor **106** is read by A/D converter **104** and passed to CPU **110**. Non-volatile memory **102** is coupled to CPU **110** and stores calibration values and long term history information. Counter-timer **104** is also coupled to CPU **110** and times the LED on times and the LED off times.

The light output of an LED can be described with the following equation using an experimentally derived figure-of-merit T_0:

$$LOP(T_j) = K_L e^{\left[\frac{-(T_j - T_c)}{T_0}\right]} \qquad \text{Equation 1}$$

where LOP(T) is the light output when the p-n junction of the LED is at temperature T_j and K_L is a measured constant that corresponds to the light output when the p-n junction of the LED is at T_c. T_0 is determined by measuring the relative light output at numerous junction temperatures and then applying an exponential fit to determine the T_0 for that particular device. The above equation describes light output in terms of the p-n junction temperature. Unfortunately, this temperature depends on a number of other factors including the ambient temperature, the short and long-term

on-off histories of the LED, the forward voltage, forward current, LED efficiency, and the thermal time constant of the LED. The short term on-off history of the LED is particularly important because it determines the starting temperature of the LED each time it is turned on or turned off. The long-term history of the LED is not as large a factor, but still may affect the brightness of the LED by as much as 3% over several years. When an LED is on, the junction temperature follows a heating curve that resembles:

$$T_j = \left(T_\infty - T_{on}\right)\left[1 - e^{\frac{-t}{\tau}}\right] + T_{on} \qquad \text{Equation 2}$$

where T_{on} is the starting temperature of the junction when the LED is turned on, T_∞ is the steady-state junction temperature that the junction would reach after the LED is on a long time and τ is the thermal time constant of the LED. When an LED is off, the junction temperature follows a cooling curve that resembles:

$$T_j = (T_{off} - T_a)e^{\frac{-t}{\tau}} + T_a \qquad \text{Equation 3}$$

where T_{off} is the starting temperature of the junction when the LED is turned off, T_a is the ambient air temperature and τ is the thermal time constant of the LED.

Over the long-term lifetime of an LED, its brightness diminishes slightly. The percent of light output after time t when compared to original light output can be expressed as:

$$\%LOP(t) = \frac{K_D t}{100}\% \qquad \text{Equation 4}$$

where K_D is a constant that is on the order of 10^{-3} when t is in hours of on time. K_D may be different for each LED, however, value can be chosen through experimentation or other means that can be used to produce an adequate

approximation of the long-term brightness degradation for a particular type, make, or model of LED.

FIG. 2 is a flowchart illustrating steps used to calculate illumination and exposure. In a step **202**, the ambient temperature is measured. If these steps are performed on the system of Fig. 1, this would be done by ambient temperature sensor **106** and A/D converter **108** under the control of, and the results passed to, CPU **110**. In a step **204**, the junction temperature is determined. In the preferred embodiment, this is done using Equation 3, Equation 4, a previous junction temperature value, and the on and off times of the illumination source since the last time the junction temperature was determined. If the illumination source has been off for a long time relative to the thermal time constant of the illumination source, then the junction temperature is the ambient temperature and these equations need not be used. This assumption agrees with the result produced by Equation 3 with $t>>\tau$. In a step **206**, the light output is determined from the junction temperature and the long-term history. In the preferred embodiment, this is done using Equation 1 which is then derated by a percentage determined using Equation 4. In a step **208**, an exposure is determined using the light output determined in step **206**. This exposure can be determined a number of ways including dividing the light output by a constant to determine an exposure time or stepwise integrating Equation 1 over time with Equation 2 determine instantaneous junction temperatures until a desired exposure is reached.

In a step **210**, the time that the illumination source has been on is determined. . If these steps are performed on the system of Fig. 1, this would be done with information received from counter-timer **104**. In the alternative, since the CPU controls the on and off times of the illumination source, the CPU could calculate the

on time of the illumination source. In a step **212**, the illumination source on time is added to a lifetime on time total. This lifetime on time total is used in Equation 4. In a step **214**, the off time of the illumination source is determined. In a system that controls exposure by means other than turning the illumination source on and off, this

5   time may be zero in which case this step may be unnecessary. In a decision box **216**, the off time is tested against a threshold value. In a preferred embodiment, this threshold value is much greater than the thermal time constant of the illumination source. If the off time is greater than this threshold value then the process loops back to step **202** and the ambient temperature is measured again. If the off time is not

10 greater than this threshold, then the process loops back to step **204** to calculate the junction temperature again.

In the preferred embodiment, the capture exposure is adjusted by turning the LED array on for the capture exposure time. However, other methods of adjusting the capture exposure, such as opening and closing a shutter, may be used. The system

15 and method of the invention can be easily adapted to these other systems by, for example, using an off time of zero during exposure and skipping step **214** until the LED array is turned off between captures.

From the foregoing it will be appreciated that the capture exposure system and LED relative brightness model provided by the invention offers the advantages of

20 simplicity and avoids the calculation of difficult exponential equations or continuos integration by the control microprocessor. Furthermore, the system may be configured to a variety of thermal parameters or adapted to a variety of exposure control mechanisms.

Although several specific embodiments of the invention have been described and illustrated, the invention is not to be limited to the specific forms or arrangements of parts so described and illustrated. The invention is limited only by the claims.

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